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VBFNLO: A parton level Monte Carlo for processes with electroweak bosons

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DOI: <https://doi.org/10.1016/j.cpc.2009.03.006>

Posted at the Zurich Open Repository and Archive, University of Zurich

ZORA URL: <https://doi.org/10.5167/uzh-30910>

Journal Article

Accepted Version

Originally published at:

Arnold, K; Bähr, M; Bozzi, G; Campanario, F; Englert, C; Figy, T; Greiner, N; Hackstein, C; Hankele, V; Jäger, B; Klämke, G; Kubocz, M; Oleari, C; Plätzer, S; Prestel, S; Worek, M; Zeppenfeld, D (2009). VBFNLO: A parton level Monte Carlo for processes with electroweak bosons. *Computer Physics Communications*, 180(9):1661-1670.

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VBFNLO: A parton level Monte Carlo for processes with electroweak bosons

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Abstract

VBFNLO is a fully flexible parton level Monte Carlo program for the simulation of vector boson fusion, double and triple vector boson production in hadronic collisions at next-to-leading order in the strong coupling constant. VBFNLO includes Higgs and vector boson decays with full spin correlations and all off-shell effects. In addition, VBFNLO implements \mathcal{CP} -even and \mathcal{CP} -odd Higgs boson via gluon fusion, associated with two jets, at the leading-order one-loop level.

A variety of effects arising from beyond the Standard Model physics are implemented for selected processes. This includes anomalous couplings of Higgs and vector bosons and a Warped Higgsless extra dimension model. The program offers the possibility to generate Les Houches Accord event files for all processes available at leading order.

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1 Introduction

The physics potential of the TEVATRON and even more of the LHC relies, to a large extent, on our ability to provide accurate cross section predictions both for signal and background processes. The latter are often generated by QCD interactions followed by weak transitions of partons to vector bosons. A precise description of such hard QCD production processes is needed, as well as a method for simulating the measurable hadronic final states. Reaching these goals requires next-to-leading order (NLO) QCD calculations presented in the form of parton level Monte Carlo (MC) generators which are an efficient solution when it comes to final states characterized by a high number of jets and/or identified particles. When kinematical cuts are imposed, as is mandatory for processes involving QCD radiation, analytical phase space integration becomes impractical and

implementation of results in the form of Monte Carlo programs becomes the method of choice.

VBFNLO is a fully flexible MC program for vector boson fusion (VBF), double and triple vector boson production processes at NLO QCD accuracy. Since real emission processes are part of the NLO cross sections, VBFNLO provides the possibility to calculate cross sections for the corresponding process with one additional jet at leading order (LO) in the strong QCD coupling. In addition, the simulation of \mathcal{CP} -even and \mathcal{CP} -odd Higgs boson production in gluon fusion, associated with two additional jets, is implemented at leading order in the strong coupling with the full top- and bottom-quark mass dependence in a generic two-Higgs-doublet model. Several models for anomalous couplings of Higgs- and vector bosons and a Warped Higgsless extra dimension model have been implemented.

Arbitrary cuts can be specified as well as various scale choices. Any currently available parton distribution function (PDF) set can be used through the LHAPDF library. For processes implemented at leading order, the program is capable of generating event files in the Les Houches Accord (LHA) format.

2 Processes

In the following sections, we describe all production processes and decay modes implemented in VBFNLO, together with references to a more detailed discussion of the underlying calculations.

In the phase space regions which are accessible at hadron colliders, VBF reactions are dominated by t -channel electroweak gauge boson exchange. In VBFNLO therefore s -channel exchange contributions and kinematically suppressed fermion interference contributions [1–3] are disregarded. Throughout, we consider only decays of the weak bosons into different lepton generations, such as $ZZ \rightarrow \ell^+\ell^-\ell'^+\ell'^-$. Results for leptonic final states with any combination of leptons (e.g., $\ell^+\ell^-\ell^+\ell^-$) can be obtained thereof by multiplying the respective results with appropriate combinatorial factors. Numerically small contributions from Pauli-interference effects for identical charged leptons are disregarded.

2.1 VBF Higgs production in association with two jets

Hjj production via VBF mainly proceeds via electroweak quark-quark scattering processes like $qq' \rightarrow qq'H$ and crossing related reactions. In VBFNLO, tree level cross sections and NLO QCD corrections to the t -channel production process are provided. The subsequent decay of the Higgs boson is simulated in the narrow width approximation (NWA). For the $H \rightarrow W^+W^-$ and the $H \rightarrow ZZ$ modes, full off-shell effects and spin correlations of the decay leptons are included. The available production process and the decay modes are listed with the corresponding process IDs in Table 1. Details of the calculation can be found in Ref. [4].

2.2 VBF Higgs production in association with three jets

Adding an extra parton to the Higgs production processes of Sec. 2.1 gives rise to $Hjjj$ final states. The corresponding cross sections are implemented at NLO QCD accuracy in VBFNLO. A list of all available modes and corresponding process IDs is given in Table 2. Details of the calculation can be found in Ref. [5].

PROCID	PROCESS
100	$pp \rightarrow H jj$
101	$pp \rightarrow H jj \rightarrow \gamma\gamma jj$
102	$pp \rightarrow H jj \rightarrow \mu^+\mu^- jj$
103	$pp \rightarrow H jj \rightarrow \tau^+\tau^- jj$
104	$pp \rightarrow H jj \rightarrow b\bar{b} jj$
105	$pp \rightarrow H jj \rightarrow W^+W^- jj \rightarrow \ell^+\nu_\ell\ell'^-\bar{\nu}_{\ell'} jj$
106	$pp \rightarrow H jj \rightarrow ZZ jj \rightarrow \ell^+\ell^-\ell'^+\ell'^- jj$
107	$pp \rightarrow H jj \rightarrow ZZ jj \rightarrow \ell^+\ell^-\nu_\ell\bar{\nu}_{\ell'} jj$

Table 1: *Process IDs for $pp \rightarrow Hjj$ production via weak boson fusion at NLO QCD accuracy.*

PROCID	PROCESS
110	$pp \rightarrow H jjj$
111	$pp \rightarrow H jjj \rightarrow \gamma\gamma jjj$
112	$pp \rightarrow H jjj \rightarrow \mu^+\mu^- jjj$
113	$pp \rightarrow H jjj \rightarrow \tau^+\tau^- jjj$
114	$pp \rightarrow H jjj \rightarrow b\bar{b} jjj$
115	$pp \rightarrow H jjj \rightarrow W^+W^- jjj \rightarrow \ell^+\nu_\ell\ell'^-\bar{\nu}_{\ell'} jjj$
116	$pp \rightarrow H jjj \rightarrow ZZ jjj \rightarrow \ell^+\ell^-\ell'^+\ell'^- jjj$
117	$pp \rightarrow H jjj \rightarrow ZZ jjj \rightarrow \ell^+\ell^-\nu_\ell\bar{\nu}_{\ell'} jjj$

Table 2: *Process IDs for $pp \rightarrow Hjjj$ production via weak boson fusion at NLO QCD accuracy.*

2.3 VBF production of a vector boson and two jets

Vector boson fusion processes can also produce final states with two leptons plus two jets, which are generically referred to as “VBF Zjj and $W^\pm jj$ production”. These reactions are implemented to NLO QCD accuracy in VBFNLO, see Table 3. Details of the calculation can be found in Ref. [6].

2.4 VBF production of two vector bosons and two jets

The production of four leptons plus two jets in the final states at order $\mathcal{O}(\alpha^6)$ is dominated by VBF contributions. In VBFNLO, all resonant and non-resonant t -channel exchange contributions giving rise to a specific leptonic final state are considered. For simplicity, we refer to these reactions as “VBF W^+W^-jj , $ZZjj$, and $W^\pm Zjj$ production”. Finite width effects of the weak bosons and spin correlations of the decay leptons are fully

PROCID	PROCESS
120	$pp \rightarrow Z jj \rightarrow \ell^+ \ell^- jj$
121	$pp \rightarrow Z jj \rightarrow \nu_\ell \bar{\nu}_\ell jj$
130	$pp \rightarrow W^+ jj \rightarrow \ell^+ \nu_\ell jj$
140	$pp \rightarrow W^- jj \rightarrow \ell^- \bar{\nu}_\ell jj$

Table 3: *Process IDs for Zjj and $W^\pm jj$ production via weak boson fusion at NLO QCD accuracy.*

PROCID	PROCESS
200	$pp \rightarrow W^+ W^- jj \rightarrow \ell^+ \nu_\ell \ell'^- \bar{\nu}_{\ell'} jj$
210	$pp \rightarrow ZZ jj \rightarrow \ell^+ \ell^- \ell'^+ \ell'^- jj$
211	$pp \rightarrow ZZ jj \rightarrow \ell^+ \ell^- \nu_{\ell'} \bar{\nu}_{\ell'} jj$
220	$pp \rightarrow W^+ Z jj \rightarrow \ell^+ \nu_\ell \ell'^+ \ell'^- jj$
230	$pp \rightarrow W^- Z jj \rightarrow \ell^- \bar{\nu}_\ell \ell'^+ \ell'^- jj$

Table 4: *Process IDs for $W^+ W^- jj$, $ZZjj$ and $W^\pm Zjj$ production via weak boson fusion at NLO QCD accuracy.*

retained. The available processes and corresponding process IDs are listed in Table 4. Details of the calculation can be found in Refs. [7–9].

2.5 Double and triple vector boson production

The production of four- and six-lepton final states mainly proceeds via double and triple vector boson production with subsequent decays. In VBFNLO, the processes listed in Table 5 are implemented to NLO QCD accuracy, including full off-shell effects and spin correlations of the final state leptons. Details of the calculation can be found in Refs. [10, 11].

2.6 Higgs production in gluon fusion with two jets

\mathcal{CP} -even and \mathcal{CP} -odd Higgs boson production in gluon fusion, associated with two additional jets, is a process which first appears at the 1-loop level which, therefore, is counted as leading order in the strong coupling. This process is simulated including the full mass dependence of the top and bottom quark running in the loop of a generic two-Higgs-doublet model. The relevant process ID is given in Table 6. Details of the calculation can be found in Refs. [12–16].

PROCID	PROCESS
300	$pp \rightarrow W^+W^- \rightarrow \ell_1^+ \nu_{\ell_1} \ell_2^- \bar{\nu}_{\ell_2}$
400	$pp \rightarrow W^+W^-Z \rightarrow \ell_1^+ \nu_{\ell_1} \ell_2^- \bar{\nu}_{\ell_2} \ell_3^+ \ell_3^-$
410	$pp \rightarrow ZZW^+ \rightarrow \ell_1^+ \ell_1^- \ell_2^+ \ell_2^- \ell_3^+ \nu_{\ell_3}$
420	$pp \rightarrow ZZW^- \rightarrow \ell_1^+ \ell_1^- \ell_2^+ \ell_2^- \ell_3^- \bar{\nu}_{\ell_3}$
430	$pp \rightarrow W^+W^-W^+ \rightarrow \ell_1^+ \nu_{\ell_1} \ell_2^- \bar{\nu}_{\ell_2} \ell_3^+ \nu_{\ell_3}$
440	$pp \rightarrow W^-W^+W^- \rightarrow \ell_1^- \bar{\nu}_{\ell_1} \ell_2^+ \nu_{\ell_2} \ell_3^- \bar{\nu}_{\ell_3}$

Table 5: *Process IDs for the W^+W^- , WWZ , ZZW and WWW production processes at NLO QCD accuracy.*

PROCID	PROCESS
4100	$pp \rightarrow H jj$

Table 6: *Process ID for the LO Higgs plus 2 jets production via gluon fusion.*

3 Installing VBFNLO

The source code of the current version of VBFNLO can be downloaded from the VBFNLO web-page

<http://www-itp.particle.uni-karlsruhe.de/vbfno/>

and includes a GNU conforming build system for portability and an easy build and installation procedure.

3.1 Prerequisites

The basic installation requires GNU `make`, a FORTRAN77¹ and a C++ compiler. VBFNLO offers the possibility to use the LHAPDF² library for parton distribution functions. In case the simulation of Kaluza-Klein resonances should be enabled, an installation of the GNU Scientific Library (GSL)³ is required.

3.2 Build and installation

After unpacking the source archive and entering the source directory, the `configure` script can be invoked with several options, a complete list being available via `./configure -help`. Among these, the most important ones are:

¹The following compilers have been tested: `g77` and `gfortran`

²<http://projects.hepforge.org/lhapdf/>

³<http://www.gnu.org/software/gsl/>

- `--prefix=[path]`
Install VBFNLO in the location given by `[path]`.
- `--enable-processes=[list]`
By default, the code for all available processes is compiled. Optionally, `[list]` gives a comma-separated list of selected processes to be compiled. Possible process names are:

<code>vbf</code>	Vector boson fusion processes
<code>diboson</code>	Double gauge boson production
<code>triboson</code>	Triple gauge boson production
<code>hjjj</code>	Higgs boson plus three jet production in vector boson fusion
<code>ggf</code>	Higgs boson plus two jets via gluon fusion
- `--disable-nlo`
Disable the next-to-leading order QCD corrections. With this option, compilation time is shortened.
- `--enable-kk`
Enable simulation of Kaluza-Klein resonances. Disabled by default, the Kaluza-Klein option requires the installation of the GNU Scientific Library to be specified via `--with-gsl`.
- `--with-LHAPDF=[path]`
Enable the usage of LHAPDF instead of the built-in PDF sets. Disabled by default. `[path]` specifies the location of the LHAPDF installation.
- `--with-gsl=[path]`
Enable usage of the GNU Scientific Library. `[path]` specifies the location of the GSL installation.

Once `configure` finished successfully, the `make` and `make install` commands will compile and install VBFNLO, respectively.

3.3 Source and installation directory layout

The VBFNLO source tree contains the following subdirectories:

- `amplitudes/`: Routines to calculate matrix elements for the processes provided.
- `doc/`: The source of this manual.
- `helas/`: HELAS [17] subroutines used to calculate helicity amplitudes.
- `loops/`: One-loop tensor integrals up to five-point functions.
- `PDFsets/`: Built-in parton distributions (CTEQ6L1 and CTEQ6M, [18]).
- `phasespace/`: Specialized phasespace generators for the processes provided.
- `src/`: Source code of the main programs and input files.
- `utilities/`: Routines for administrative tasks, cuts, scale choices and interfaces.

The source does not need to be modified to change the simulation parameters. VBFNLO offers several kinematical cuts and scale choices. This is illustrated in Sec. 4. In addition, it provides a few basic histograms. Cuts, histograms and scale choices not already provided may be added in the `utilities/cuts.F`, `utilities/histograms.F` and `utilities/scales.F` files.

The installation is performed in a standard UNIX-layout, i.e. the directory specified with the `--prefix` option of the `configure` script contains the following directories:

- `bin/`: `vbfnlo` and `ggflo` executables.
- `include/VBFNLO/`: VBFNLO header files.
- `lib/VBFNLO/`: VBFNLO modules as dynamically loadable libraries. These can also be used independently from one of the main programs.
- `share/VBFNLO/`: Input files and internal PDF tables.

3.4 Running the program

Both the `vbfnlo` and `ggflo` executables contained in the `bin` directory of the installation path do look for input files in their current working directory. An alternative path to input files may be specified explicitly by passing the `input=path` argument to the programs, with `path` denoting the full path where input files are located.

The input files contained in the `share/VBFNLO` directory are meant to represent default settings and should not be changed. We therefore recommend to symbolically link the desired executable and copy the input files to a separate directory. Here, special settings may be chosen in the input files and the program can be run in that directory without specifying further options.

3.5 Bug reports

Please report any problems to

`vbfnlo@particle.uni-karlsruhe.de`

including a short report with which configure options VBFNLO has been built, as well as the versions of compilers and external libraries used.

3.6 License

VBFNLO is distributed under the GNU General Public License (GPL) version 2. This ensures that the source code will be available to users, grants them the freedom to use and modify the program and sets out the conditions under which it can be redistributed. However, it was developed as part of an academic research project and is the result of many years of work by the authors, which raises various issues that are not covered by the legal framework of the GPL. It is therefore distributed together with a set of guidelines⁴, which originally have been formulated and agreed on by the MCnet collaboration for event generator software.

⁴These guidelines are contained in the `GUIDELINES` file distributed with the release.

4 Input files and parameters

VBFNLO is steered through the following input files:

- `vbfnlo.dat`: General parameters for a run.
- `ggflo.dat`: Additional parameters for the `ggflo` program.
- `cuts.dat`: Values for kinematical cuts.
- `anom_HVV.dat`: Parameters for anomalous Higgs couplings.
- `anom_WW.dat`: Parameters for anomalous triple gauge boson couplings.
- `random.dat`: Seed for the random number generator.

The following subsections will give a detailed description of all available parameters.

4.1 `vbfnlo.dat` — general parameters

- `PROCESS`: Process ID as described in Sec. 2.
- `LOPROCESS_PLUS_JET`: If set to true, the leading order process with one additional jet is generated, i.e. only the real radiation contribution is generated. This option is available for all but gluon fusion processes.
- `LEPTONS`: Choice of the final state leptons according to the MC particle numbering scheme [19]. If the selected configuration is not available, default values are used.
- `LO_ITERATIONS`: Sets the number of iterations for the integration of LO cross sections. Usually more than one iteration is used in order to adapt the integration grid and thus improve the efficiency of the MC integration algorithm⁵. For an adapted grid file (see `LO_GRID`) this parameter can be set to 1. Default is 4.
- `NLO_ITERATIONS`: Analogous to `LO_ITERATIONS`, but for the real emission part of an NLO calculation. Since the corresponding phase space is different from the LO configuration, a second independent MC integration has to be performed. Default is 4.
- `LO_POINTS`: Determines the number of phase space points that are generated in each iteration. In the last iteration there are 2^N points, where $N=\text{LO_POINTS}$. In each previous iteration, the number of points is half the value of the following one. Example: For 4 iterations (`LO_ITERATIONS` = 4) and `LO_POINTS` = 20, there are 2^{17} generated points in the first, 2^{18} in the second, 2^{19} in the third and $2^{20} \approx 10^6$ in the last iteration⁶. Default is $N = 20$.
- `NLO_POINTS`: Similar to `LO_POINTS`, but for the real emission part of a NLO calculation.

⁵For all NLO calculations the virtual contributions are calculated using the already optimized leading order grid.

⁶The virtual contributions are calculated for 2^N points only.

- **LO_GRID**: Sets the name of the grid files that are generated at the end of each iteration. Choosing **name** as input parameter, in each iteration X a grid file **name.out.X** will be produced. If a grid file **name** is already present in the working directory, the program reads in this file when executed.
- **NLO_GRID**: Similar to **LO_GRID**, but for the real emission part of a NLO calculation.
- **NLO_SWITCH**: Switch for the NLO part of a process, if available. If set to **.true.**, cross sections and histograms are calculated to NLO QCD accuracy. Default is set to **.false.**
- **ECM**: The center-of-mass energy \sqrt{s} of the collider, measured in GeV. Default is 14000 GeV.
- **BEAM1**, **BEAM2**: Define the type of particle of each beam. Possible options are $+1$ for proton beams and -1 for anti-proton beams. Default is proton-proton collisions, $(+1, +1)$.
- **ID_MUF**: Choice of the factorization scale. See Table 7 for a list of available options. Default is 0.
- **ID_MUR**: Choice of the renormalization scale. See Table 8 for a list of available options. Default is 0.

ID_MUF	FACTORIZATION SCALE	PROCESS CLASS
0	user defined constant scale set by MUF_USER	all
1	momentum transfer of exchanged W/Z boson	vbf
2	$\min(p_T(j_1), p_T(j_2))$	vbf
3	invariant mass of VV system	diboson
4	invariant mass of VVV system	triboson
5	$\sqrt{p_T(j_1) \times p_T(j_2)}$	ggf

Table 7: Factorization scale options.

- **MUF_USER**: If **ID_MUF** is set to 0, this parameter sets the user defined constant factorization scale measured in GeV. Default is 100 GeV.
- **MUR_USER**: If **ID_MUR** is set to 0, this parameter sets the user defined constant renormalization scale measured in GeV. Default is 100 GeV.
- **XIF**: Factor by which the factorization scale is multiplied. May be used to analyze the scale dependence of differential cross sections. Default is 1.0.
- **XIR**: Factor by which the renormalization scale is multiplied. May be used to analyze the scale dependence of differential cross sections. Default is 1.0.

ID_MUR	RENORMALIZATION SCALE	PROCESS CLASS
0	user defined constant scale set by MUR_USER	all
1	momentum transfer of exchanged W/Z boson	vbf
2	$\min(p_T(j_1), p_T(j_2))$	vbf
3	invariant mass of VV system	diboson
4	invariant mass of VVV system	triboson
5	$\alpha_s^4 = \alpha_s(p_T(j_1)) \times \alpha_s(p_T(j_2)) \times \alpha_s^2(m_H)$	ggf

Table 8: Renormalization scale options.

4.2 vbfno.dat — physics parameters

- **HMASS**: Standard Model Higgs boson mass in GeV. Default value is 120 GeV.
- **TOPMASS**: Top quark mass in GeV. Default value is 172.4 GeV.
- **BOTTOMMASS**: Bottom quark pole mass in GeV, used in the calculation of the Higgs width and branching ratios as well as in the heavy quark loop in the gluon fusion process. Default value is 4.855 GeV.
- **CHARMMASS**: Charm quark pole mass in GeV used in the calculation of the Higgs width and branching ratios. Default value is 1.65 GeV.
- **ALFA_S**: Strong coupling constant as used in the calculation of W, Z and H widths. The strong coupling constant used in the matrix element calculations is printed out during run time. Default value is 0.1176.
- **EWScheme**: Sets the scheme for the calculation of electroweak parameters. A summary of the four available options is given in Table 9. Default value is 3.
- **FERMI_CONST**: Fermi constant, used as input for the calculation of electroweak parameters. Default value is $1.16637 \times 10^{-5} \text{ GeV}^{-2}$.
- **ALFA**: Fine structure constant, used as input for **EWScheme** = 1 and 4. Within the other schemes this parameter is calculated. Default value is $7.2973525376 \times 10^{-3}$.
- **SIN2W**: Sinus squared of the weak mixing angle. Used as input for **EWScheme** = 2 and 4. Within the other schemes this parameter is calculated. Default value is 0.23119.
- **WMASS**: W boson mass in GeV. Default value is 80.398 GeV.
- **ZMASS**: Z boson mass in GeV. Default value is 91.1876 GeV.
- **ANOM_CPL**: Options for anomalous Higgs and gauge boson couplings. These are available for the Hjj and W^+W^-jj production processes in VBF. Default is set to `.false..`

EWScheme	Parameter	Default Value	Input/Calculated
1	FERMI_CONST	$1.16637 \times 10^{-5} \text{ GeV}^{-2}$	INPUT
	ALFA	$7.2973525376 \times 10^{-3}$	INPUT
	SIN2W	0.23110323	CALCULATED
	WMASS	79.9595 GeV	CALCULATED
	ZMASS	91.1876 GeV	INPUT
2	FERMI_CONST	$1.16637 \times 10^{-5} \text{ GeV}^{-2}$	INPUT
	ALFA	$7.7602239787 \times 10^{-3}$	CALCULATED
	SIN2W	0.23119	INPUT
	WMASS	79.9544 GeV	CALCULATED
	ZMASS	91.1876 GeV	INPUT
3	FERMI_CONST	$1.16637 \times 10^{-5} \text{ GeV}^{-2}$	INPUT
	ALFA	$7.5562544251 \times 10^{-3}$	CALCULATED
	SIN2W	0.22264585	CALCULATED
	WMASS	80.3980 GeV	INPUT
	ZMASS	91.1876 GeV	INPUT
4	FERMI_CONST	$1.16637 \times 10^{-5} \text{ GeV}^{-2}$	INPUT
	ALFA	$7.2973525376 \times 10^{-3}$	INPUT
	SIN2W	0.23119	INPUT
	WMASS	80.398 GeV	INPUT
	ZMASS	91.1876 GeV	INPUT

Table 9: *Electroweak input parameter schemes.*

- **KK_MOD**: Option for the Warped Higgsless Model. It is available for all $VVjj$ production modes in VBF. Default is set to `.false..`

4.3 vbfno.dat – parameters for event output

VBFNLO generates parton level events according to the most recent Les Houches Accord (LHA) format [20] for processes available at leading order.

- **LHA_SWITCH**: Switch on or off output of LHA event files. Default is set to `.false..`
- **UNWEIGHTING_SWITCH**: Option for event weights. If set to `.true..`, events are unweighted (event weight = +1). If set to `.false..`, events are weighted. Default is set to `.false..`

- **PRENEVUNW**: The number of events used in the last iteration in order to calculate/estimate the premaximal weight which is needed in the first step of the unweighting procedure. Default is 1000. After all events are unweighted, the maximal weight is again calculated and a reweighting procedure is applied.
- **TAUMASS**: Option to include the mass of τ leptons in the LHA file. So far this option only works for the vbf processes. Default is set to `.false..`

4.4 vbfno.dat — PDF parameters

VBFNLO may use built-in parton distribution functions (PDF) or the LHAPDF library.

- **PDF_SWITCH**: Option to choose which PDFs are used. If set to 0, built-in PDFs (CTEQ6L1 for LO and CTEQ6M for NLO calculations) are used [18]. If set to 1, an interface to LHAPDF is provided via LHAGLUE [21].
- **LO_PDFSET**: LHAGLUE number for the LO PDF set, see PDFsets.index or Ref. [21]. Default is 10042 (CTEQ6L1).
- **NLO_PDFSET**: LHAGLUE number for the NLO PDF set, see PDFsets.index or Ref. [21]. Default is 10000 (CTEQ6M).

4.5 vbfno.dat — parameters for histograms

VBFNLO provides output for histograms in the following formats: TOPDRAWER⁷, ROOT⁸ and GNUPLOT⁹.

- **ROOT**: Enable output of histograms in ROOT format. Default is set to `.false..`
- **TOP**: Enable output of histograms in TOPDRAWER format. Default is set to `.false..`
- **GNU**: Enable output of histograms in GNUPLOT format. Default is set to `.true..`
- **REPLACE**: Switch to overwrite existing histogram output files. Default is set to `.true..`
- **ROOTFILE**: Name of the ROOT output file. Default is `histograms`.
- **TOPFILE**: Name of the TOPDRAWER output file. Default is `histograms`.
- **GNUFILE**: Name of the GNUPLOT output file. Default is `histograms`.

4.6 cuts.dat — parameters for kinematical cuts

Jet-specific cuts:

- **RJJ_MIN**: Minimum separation of two identified jets, $\Delta R_{jj} = \sqrt{\Delta y_{jj}^2 + \Delta \phi_{jj}^2}$, used by the k_\perp jet finding algorithm [22] which combines all partons. Default is 0.8.

⁷<http://www.pa.msu.edu/reference/topdrawer-docs/>

⁸<http://root.cern.ch/>

⁹<http://www.gnuplot.info/>

- **Y_P_MAX**: Maximum allowed pseudorapidity for final state partons. Default is 5.0.
- **PT_JET_MIN**: Minimum transverse momentum for identified jets. Default is 20 GeV.
- **Y_JET_MAX**: Maximum allowed rapidity for identified jets. Default is 4.5.

Lepton specific cuts:

- **Y_L_MAX**: Maximum pseudorapidity for charged leptons. Default is 2.5.
- **PT_L_MIN**: Minimum transverse momentum for charged leptons. Default is 10 GeV.
- **MLL_MIN**: Minimum invariant mass for any combination of oppositely charged leptons. Default is 15 GeV.
- **RLL_MIN**: Minimum separation of charged lepton pairs, $\Delta R_{\ell\ell}$. Default is 0.
- **RLL_MAX**: Maximum separation of charged lepton pairs, $\Delta R_{\ell\ell}$. Default is 50.

Photon specific cuts:

- **Y_G_MAX**: Maximum pseudorapidity for photons. Default is 1.5.
- **PT_G_MIN**: Minimum transverse momentum for photons. Default is 20 GeV.
- **RGG_MIN**: Minimum separation of photon pairs, $\Delta R_{\gamma\gamma}$. Default is 0.
- **RGG_MAX**: Maximum separation of photon pairs, $\Delta R_{\gamma\gamma}$. Default is 50.

Additional cuts:

- **RJL_MIN**: Minimum separation of an identified jet and a charged lepton, $\Delta R_{j\ell}$. Default is 0.
- **RJG_MIN**: Minimum separation of an identified jet and a photon, $\Delta R_{j\gamma}$. Default is 0.
- **RLG_MIN**: Minimum separation of a charged lepton and a photon, $\Delta R_{\ell\gamma}$. Default is 0.

VBF specific cuts¹⁰:

- **ETAJJ_MIN**: Minimum required pseudorapidity gap, $\Delta\eta_{jj}$, between two tagging jets (the two leading jets in a p_T ordering). Default is 0.
- **YSIGN**: If set to `.true.`, the two tagging jets are required to be found in the opposite detector hemispheres. Default is `.false..`
- **LRAPIDGAP**: If set to `.true.` all charged leptons are required to lie between the two tagging jets in rapidity. Default is `.false..`
- **DELY_JL**: Minimum rapidity distance of the charged leptons from the tagging jets, if **LRAPIDGAP** is set to `.true..` Default is 0.

¹⁰These apply only to **vbf** and **ggf** processes.

- **GRAPIDGAP**: If set to `.true.` all photons are required to lie between the two tagging jets in rapidity. Default is `.false..`
- **DELY_JG**: Minimum rapidity distance of photons from tagging jets, if **GRAPIDGAP** is set to `.true..` Default is 0.
- **MDIJ_MIN**: Minimum dijet invariant mass of two tagging jets. Default is 0 GeV.
- **MDIJ_MAX**: Maximum dijet invariant mass of two tagging jets. Default is 14000 GeV.
- **JVETO**: If set to `.true.`, a central jet veto is applied. Default is `.false..`
- **DELY_JVETO**: Minimum rapidity separation of a central jet from two tagging jets. Default is 0.
- **YMAX_VETO**: Maximum pseudorapidity of a central jet. Default is 4.5.
- **PTMIN_VETO**: Minimum transverse momentum of a central jet. Default is 10 GeV.

4.7 Parameters for anomalous couplings

VBFNLO supports anomalous HVV couplings, where $V = W, Z, \gamma$, in both the production and the decay of a Higgs boson in VBF type reactions, i.e. for PROCIDs 100-107. The anomalous HVV couplings can be parameterized in the `anom_HVV.dat` input file. Moreover, the triple and quartic anomalous gauge boson couplings for the VBF process $pp \rightarrow W^+W^-jj(j)$ are included [23]. These can be set in the `anom_WW.dat` file.

4.7.1 `anom_HVV.dat` – anomalous HVV couplings

Among the anomalous coupling input parameters, the user can choose between three different parameterizations.

1. A parameterization in terms of couplings in the effective Lagrangian approach. In VBFNLO effective dimension five operators are included corresponding to

$$\mathcal{L}_{\text{eff}}^{d=5} = \frac{g_{5e}^{HVV}}{\Lambda_{5e}} HV_{\mu\nu}^+ V^{-\mu\nu} + \frac{g_{5o}^{HVV}}{\Lambda_{5o}} H\tilde{V}_{\mu\nu}^+ V^{-\mu\nu}, \quad (1)$$

where the subscript e or o refers to the \mathcal{CP} -even or \mathcal{CP} -odd nature of the individual operators [24].

- **PARAMETR1**: Parameter which switches on the effective Lagrangian parameterization Eq. (1). The default value is `.false..`
- **LAMBDA5**: Mass scales Λ_{5e} and Λ_{5o} in units of GeV with 480 GeV chosen as default.
- **G5E_HWW**, **G5E_HZZ**, **G5E_HGG**, **G5E_HGZ**: Parameters which determine the couplings g_{5e}^{HVV} of the \mathcal{CP} -even dimension five operators. Their default values are set to 0.
- **G5O_HWW**, **G5O_HZZ**, **G5O_HGG**, **G5O_HGZ**: Parameters which determine the couplings g_{5o}^{HVV} of the \mathcal{CP} -odd dimension five operators. Their default values are set to 0.

2. The parameterization of the anomalous couplings by the L3 Collaboration as given in Ref. [25]. The parameters are d , d_B , Δg_1^Z and $\Delta \kappa_\gamma$. For the \mathcal{CP} -odd operators only three parameters are needed. These are defined in analogy to the \mathcal{CP} -even ones and can be related to the coefficients f_i of the operators \mathcal{O}_i in the effective Lagrangian as described in Ref. [26] in the following way:

$$\begin{aligned}
d &= -\frac{m_W^2}{\Lambda^2} f_{WW}, & \tilde{d} &= -\frac{m_W^2}{\Lambda^2} f_{\tilde{W}W}, \\
d_B &= -\frac{m_W^2}{\Lambda^2} \frac{\sin^2 \theta_w}{\cos^2 \theta_w} f_{BB}, & \tilde{d}_B &= -\frac{m_W^2}{\Lambda^2} \frac{\sin^2 \theta_w}{\cos^2 \theta_w} f_{\tilde{B}B}, \\
\Delta \kappa_\gamma &= \kappa_\gamma - 1 = \frac{m_W^2}{2\Lambda^2} (f_B + f_W), & \tilde{\kappa}_\gamma &= \frac{m_W^2}{2\Lambda^2} f_{\tilde{B}}, \\
\Delta g_1^Z &= g_1^Z - 1 = \frac{m_Z^2}{\Lambda^2} \frac{f_W}{2}
\end{aligned} \tag{2}$$

- **PARAMETR2**: Parameter which switches on the above mentioned parameterization. The default value is `.false..`
 - **D_EVEN**, **DB_EVEN**, **DG1Z_EVEN**, **DKGAM_EVEN**: Parameters which are the \mathcal{CP} -even couplings in this parameterization with default 0.
 - **D_ODD**, **DB_ODD**, **KGAM_ODD**: Parameters which are the \mathcal{CP} -odd couplings in this parameterization with default values equal to 0.
 - **HVV1**: Parameter which determines which anomalous HVV couplings are used for the run. For **HVV1** = 0, only the $HZ\gamma$ couplings, for **HVV1** = 1, only the $H\gamma\gamma$ coupling, for **HVV1** = 2, only the HZZ coupling and for **HVV1** = 3, only the HWW coupling is used. If **HVV1** is set to 4, all possible anomalous couplings are used. This is also the default value.
3. The parameterization of the anomalous couplings in terms of coefficients f_i/Λ^2 of the operators \mathcal{O}_{WW} , \mathcal{O}_{BB} , \mathcal{O}_W and \mathcal{O}_B and their corresponding \mathcal{CP} -odd operators according to Refs. [27, 28].
- **PARAMETR3**: Parameter which switches on the parameterization stated above. The default value is `.false..`
 - **FWW_EVEN**, **FBB_EVEN**, **FW_EVEN**, **FB_EVEN**: Parameters which represent the coefficients of the \mathcal{CP} -even operators with default values equal to 0.
 - **FWW_ODD**, **FBB_ODD**, **FB_ODD**: Parameters which are the coefficients of the \mathcal{CP} -odd operators with default values 0.
 - **HVV2**: Parameter which allows to choose which anomalous HVV couplings are used. For **HVV2** = 0, only the $HZ\gamma$ coupling, for **HVV2** = 1, only the $H\gamma\gamma$ coupling, for **HVV2** = 2, only the HZZ coupling and for **HVV2** = 3, only the HWW coupling is used. If set to 4 all possible anomalous couplings are used. The default value is 4.
 - **TREEFAC**: Parameter that multiplies the HVV tensor present in the SM Lagrangian. Default is 1.
 - **LOOPFAC**: Parameter that multiplies the $HZ\gamma$ and $H\gamma\gamma$ vertices induced by SM loops. The default is chosen to be 1.

Moreover, for all parameterizations two different form factors can be chosen as described in Refs. [24, 26]. They model effective, momentum dependent HVV vertices, motivated from new physics entering with a large scale Λ at the loop level.

$$F_1 = \frac{\Lambda^2}{q_1^2 - \Lambda^2} \frac{\Lambda^2}{q_2^2 - \Lambda^2}, \quad (3)$$

$$F_2 = -2\Lambda^2 C_0(q_1^2, q_2^2, (q_1 + q_2)^2, \Lambda^2). \quad (4)$$

Here the q_i are the momenta of the vector bosons and C_0 is the scalar one-loop three point function in the notation of Ref. [29].

- **FORMFACTOR**: Parameter which switches on the above form factor parameterization. The default value is set to `.false..`
- **MASS_SCALE**: Characteristic mass scale of new physics Λ in units of GeV. The default value is 200 GeV.
- **FFAC**: Parameter which is used to select one particular form factor out of Eqs. (3) and (4). If **FFAC** = 1, the form factor F_1 is used for the parameterization. **FFAC** = 2 selects F_2 , which is also the default value.

Finally, the two parameters can be used to rescale the SM HVV couplings.

- **TREEFAC**: Parameter that multiplies the HVV tensor present in the SM Lagrangian. Default is 1.
- **LOOPFAC**: Parameter that multiplies the $HZ\gamma$ and $H\gamma\gamma$ vertices induced by SM loops. The default is chosen to be 1.

4.7.2 `anom_WW.dat` – **anomalous triple and quartic gauge boson couplings**

The triple and quartic anomalous gauge boson couplings can be set in `anom_WW.dat`. The input values are the coefficients f_i/Λ^2 of the \mathcal{CP} -even operators in the effective Lagrangian \mathcal{O}_{BW} , \mathcal{O}_{DW} , \mathcal{O}_{WWW} , \mathcal{O}_{WW} , \mathcal{O}_{BB} , \mathcal{O}_W and \mathcal{O}_B and their corresponding \mathcal{CP} -odd operators as described in Refs. [28, 30].

- **FBW**, **FDW**, **FWWW**, **FWW**, **FBB**, **FW**, **FB**: Parameters which give the values of the coefficients of the \mathcal{CP} -even operators. The default values for these parameters are 0.
- **FWWt**, **FBWt**, **FBBt**, **FWt**, **FBt**, **FWWWt**, **FDWt**: Parameters which are the coefficients of the \mathcal{CP} -odd operators. The default values for these parameters are 0.
- **OVS**: Parameter which switches on the overall factor scheme. The default value is `.false..`
- **FORMFAC**: Parameter which allows to include the form factor

$$F = \left(1 + \frac{s}{\Lambda^2}\right)^{-n}, \quad (5)$$

in the calculation, where Λ is a characteristic new physics mass scale. The default value is `.false..`

- **LAMBDA**: Parameter that gives the above scale Λ in units of GeV. Default is 2500 GeV.
- **EXPFAC**: Parameter to set the exponent n in Eq. (5) with default value 2.

4.8 `kk_input.dat` – parameters for the Warped Higgsless model

VBFNLO is capable of calculating the weak boson fusion processes $VV+2$ jets in the Warped Higgsless scenario [31] at LO and NLO QCD level (see, for example, Ref. [32] for a phenomenological application). The model parameters can be generated by VBFNLO via the input file `kk_input.dat` for a hard wired choice of the relevant five dimensional gauge parameters. The input values are

- Switch that determines whether VBFNLO should calculate the parameters needed by the model. Default is `.true..`
- Location of the UV brane for the generation of the model parameters in the Warped Higgsless Model. Default is $R = 9.75 \times 10^{-9}$, which amounts to the Kaluza-Klein excitations having masses of $m_{W_2} = 700$ GeV, $m_{Z_2} = 695$ GeV, and $m_{Z'_1} = 718$ GeV. Smaller values of R result in a heavier Kaluza-Klein spectrum.
- The maximum number of Kaluza-Klein W_k^\pm states to be included on top of the Standard Model W^\pm bosons, which correspond to $W_{k=1}^\pm$. All states $k \geq 3$ are phenomenologically irrelevant. Default is 1.
- The maximum number of Kaluza-Klein Z_k states to be included on top of the Standard Model Z boson, which corresponds to $Z_{k=1}$. All states $k \geq 3$ are phenomenologically irrelevant. Default is 1.
- The maximum number of Kaluza-Klein Z'_k bosons that are excitations of the Standard Model photon $Z'_{k=0}$. States $k \geq 2$ are phenomenologically irrelevant. Default is 1.

The explicit breaking of higher dimensional gauge invariance is balanced according to the description of [33], where also more details on the model and its implementation can be found.

VBFNLO generates the text file `kk_coupl_inp.dat`, which documents the calculated model parameters, i.e. Kaluza-Klein gauge boson masses, couplings and widths of the specified input parameters. This file can also be used as input file for advanced users who want to run the code with their own set of parameters. To that end, select `.false.` in the file `kk_input.dat`. VBFNLO will then calculate the gauge boson widths on the basis of these parameters by the decay to the lower lying states. Information on the widths and on the sum rules relating the various gauge boson couplings [34] are written to `kk_check.dat`.

4.9 `ggflo.dat` – general parameters for gluon fusion processes

In VBFNLO, the double real-emission corrections to $gg \rightarrow \phi$, which lead to $\phi+2$ jet events at order α_s^4 , are included. Here, ϕ can be a scalar (h, H) or pseudo-scalar (A) Higgs boson as in a generic two-Higgs -doublet model (2HDM) of type II. Contributions contain top- and bottom-quark triangles, boxes and pentagon diagrams, i.e. the full mass dependence of the loop induced production. Interference effects between loops with bottom and top quarks as well as between \mathcal{CP} -even and \mathcal{CP} -odd couplings of the heavy quarks are fully taken into account. An option to use the large top mass approximation, which works well for intermediate Higgs boson masses, provided that the transverse momenta of the final state partons are smaller than the top quark mass, is also implemented.

ID	MODEL DESCRIPTION
0	Toy model with settings provided by the user
1	\mathcal{CP} -even Higgs (H_{SM}) in the large top quark mass limit ($m_t \rightarrow \infty$)
2	\mathcal{CP} -odd Higgs (H_{SM}) in the large top quark mass limit ($m_t \rightarrow \infty$)
3	\mathcal{CP} -even Higgs (H_{SM}) with full mass dependence of the top quark loop
4	\mathcal{CP} -even Higgs (H_{SM}) with full mass dependence of the bottom quark loop
5	\mathcal{CP} -even Higgs (H_{SM}) with full mass dependence of the top and bottom quark loop
6	\mathcal{CP} -odd Higgs (A) with full mass dependence of the top quark loop
7	\mathcal{CP} -odd Higgs (A) with full mass dependence of the bottom quark loop
8	\mathcal{CP} -odd Higgs (A) with full mass dependence of the top and bottom quark loop
9	\mathcal{CP} -even Higgs (h) with full mass dependence of the top quark loop
10	\mathcal{CP} -even Higgs (h) with full mass dependence of the bottom quark loop
11	\mathcal{CP} -even Higgs (h) with full mass dependence of the top and bottom quark loop
12	\mathcal{CP} -even Higgs (H) with full mass dependence of the top quark loop
13	\mathcal{CP} -even Higgs (H) with full mass dependence of the bottom quark loop
14	\mathcal{CP} -even Higgs (H) with full mass dependence of the top and bottom quark loop

Table 10: *Different models for the production of a Higgs boson plus two jets via gluon fusion.*

If Higgs boson plus two jets production via gluon fusion is selected in `vbfnlo.dat`¹¹, the following additional parameters have to be adjusted:

- **PROCESSGGF**: Model ID. A summary is given in Table 10. Default is 3.
- **SUBPRQQ**: Switch for the subprocesses with quark-quark initial state. Default is set to `.true..`
- **SUBPRQG**: Switch for the subprocesses with quark-gluon initial state. Default is set to `.true..`
- **SUBPRGG**: Switch for the subprocesses with gluon-gluon initial state. Default is set to `.true..`
- **TAN_BETA**: Ratio of vacuum expectation values, $\tan \beta = v_u/v_d$ where $v^2 = v_u^2 + v_d^2$.
- **ALPHA**: Neutral Higgs boson mixing angle α , which arises when the \mathcal{CP} -even Higgs boson mass matrix is diagonalized to obtain the physical \mathcal{CP} -even Higgs boson states, h and H .

¹¹Note that this process requires usage of the `ggf10` executable program rather than the `vbfnlo` one.

5 Checks

Extensive checks for the LO and the real emission amplitudes as well as for the total LO cross sections have been performed for all processes implemented in VBFNLO. Born amplitudes and real emission diagrams have been compared with the fully automatically generated results provided by MADGRAPH [35]. Complete agreement has been found in each case. Moreover, total LO cross sections with a minimal set of cuts agree with the respective results obtained by MADEVENT¹² [36, 37] and HELAC¹³ [38, 39], a completely automatic parton level event generator based on Dyson-Schwinger recursive equations.

All LHA event files for the LO processes have been tested with HERWIG++¹⁴ [40], a general purpose Monte Carlo event generator for the simulation of hard lepton-lepton and hadron-hadron collisions.

As a final and very important test, comparisons with already published results have been made. In Ref. [41], a tuned comparison of LO and NLO QCD results for Higgs boson production via vector boson fusion at the LHC has been performed. Three different calculations have been cross checked: VBFNLO, the results of Refs. [42, 43], and the VV2H program¹⁵. For the dominant t - and u -channel contributions which are implemented in VBFNLO, good agreement has been found. For the triboson processes a comparison for the production of on-shell gauge bosons without leptonic decays has been performed with the results presented in Ref. [44]. Again, good agreement has been found. Results for the \mathcal{CP} -odd and \mathcal{CP} -even Higgs boson production via gluon fusion have been tested against FEYNARTS¹⁶ [45, 46].

6 Summary & Outlook

VBFNLO is a fully flexible partonic Monte Carlo program for vector boson fusion, double and triple vector boson production processes at NLO QCD accuracy. The simulation of \mathcal{CP} -even and \mathcal{CP} -odd Higgs boson production in gluon fusion, associated with two additional jets, is implemented at leading order (for this process only, the LO starts at one-loop level).

Future improvements are directed along two main lines of development: Further processes at NLO QCD accuracy will be included (e.g., $pp \rightarrow WW\gamma$ and $pp \rightarrow W\gamma j$) and new features will be added to the already existing processes, such as anomalous triple and quartic gauge boson couplings and Kaluza-Klein excitations. Higgs production via gluon fusion within the generic two-Higgs-doublet model will be extended to a complete simulation within the Minimal Supersymmetric Standard Model (MSSM), including full dependence on scalar top and bottom quarks masses. Matching the NLO QCD processes to a parton shower at next-to-leading logarithmic accuracy is currently in progress.

Acknowledgments

The research presented in this article was supported in part by the Deutsche Forschungsgemeinschaft via the Sonderforschungsbereich/Transregio SFB/TR-9 “Computational Par-

¹²<http://madgraph.hep.uiuc.edu/>

¹³<http://helac-phegas.web.cern.ch/helac-phegas/>

¹⁴<http://projects.hepforge.org/herwig/>

¹⁵<http://people.web.psi.ch/spira/vv2h/>

¹⁶<http://www.feynarts.de/>

ticle Physics” and the Graduiertenkolleg “High Energy Physics and Particle Astrophysics”, and in part by the National Science Foundation under Grant No. PHY05-51164.

F. Campanario acknowledges a postdoctoral fellowship of the Generalitat Valenciana (Beca Postdoctoral d’Excellència) and S. Plätzer support from the Landesgraduiertenförderung Baden-Württemberg. M. Worek was funded in part by the RTN European Programme MRTN-CT-2006-035505 HEPTOOLS - Tools and Precision Calculations for Physics Discoveries at Colliders and B. Jäger by the Initiative and Networking Fund of the Helmholtz Association, contract HA-101 ("Physics at the Terascale").

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